MORPHOLOGY AND VOLATILITY OF PARTICULATE MATTER EMITTED FROM TWO DIRECT-INJECTION ENGINES

Brian Graves, Jason Olfert, Bob Koch, Bronson Patychuk, Ramin Dastanpour, Steven Rogak

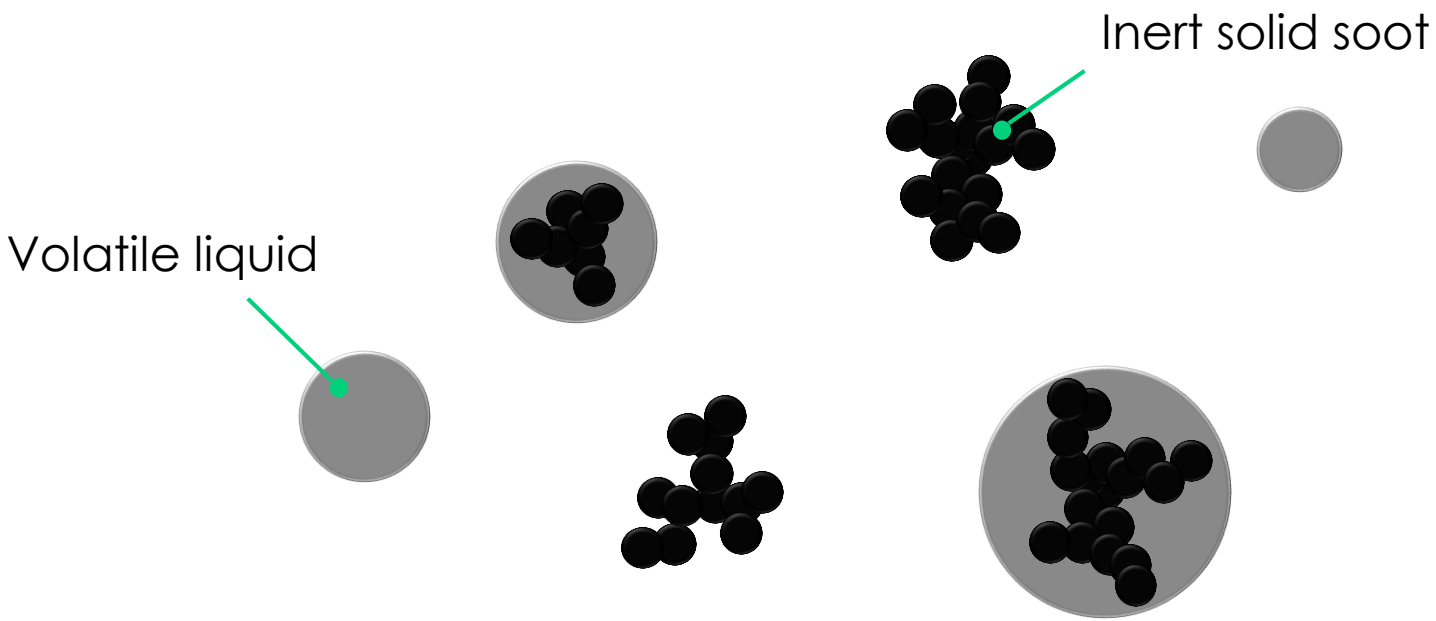
University of Alberta, Westport Innovations Inc., University of British Columbia

Cambridge Particle Meeting, 2015

July 3

PROBLEM DEFINITION AND CONTEXT

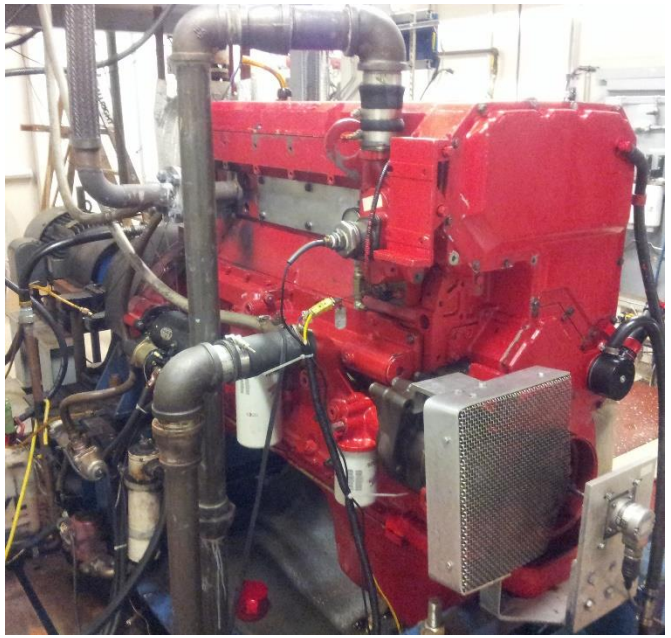
- Elemental carbon (soot) – Particulate trap
- Volatile hydrocarbons – Catalytic converter



Typical particulate matter from combustion engine

ENGINE 1 – WESTPORT HPDI

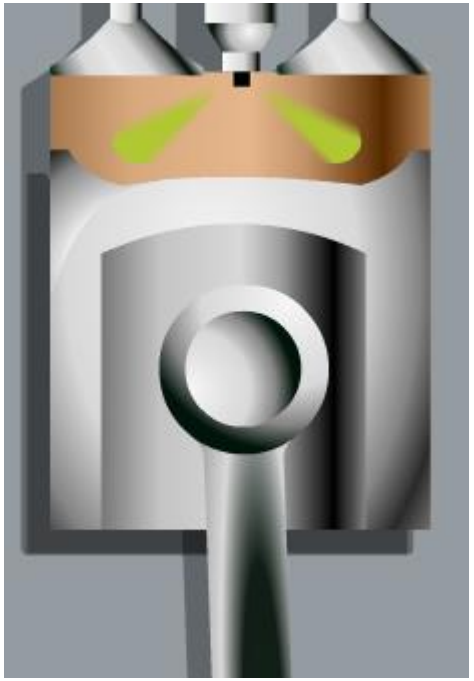
- Cummins ISX Engine
- Fitted with Westport Innovations Inc.'s high pressure direct injection (HPDI) system
- Fuelled with natural gas, diesel pilot used for ignition
- Run on a single cylinder



Compression ignition engine

ENGINE 1 – WESTPORT HPDI

a) Diesel injection



b) Natural gas injection, diesel begins to ignite (diffusion flame)

c) **Natural gas burns as a diffusion flame – not premixed**

Stages of HPDI combustion

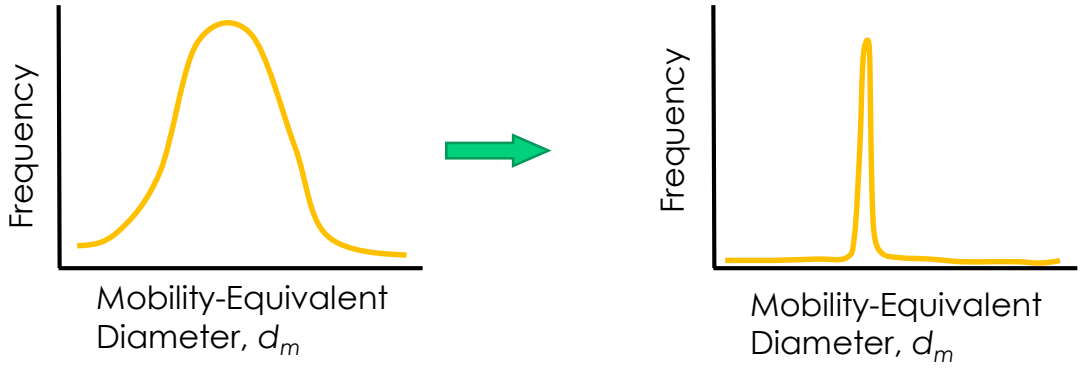
ENGINE 2 – GENERAL MOTORS GDI

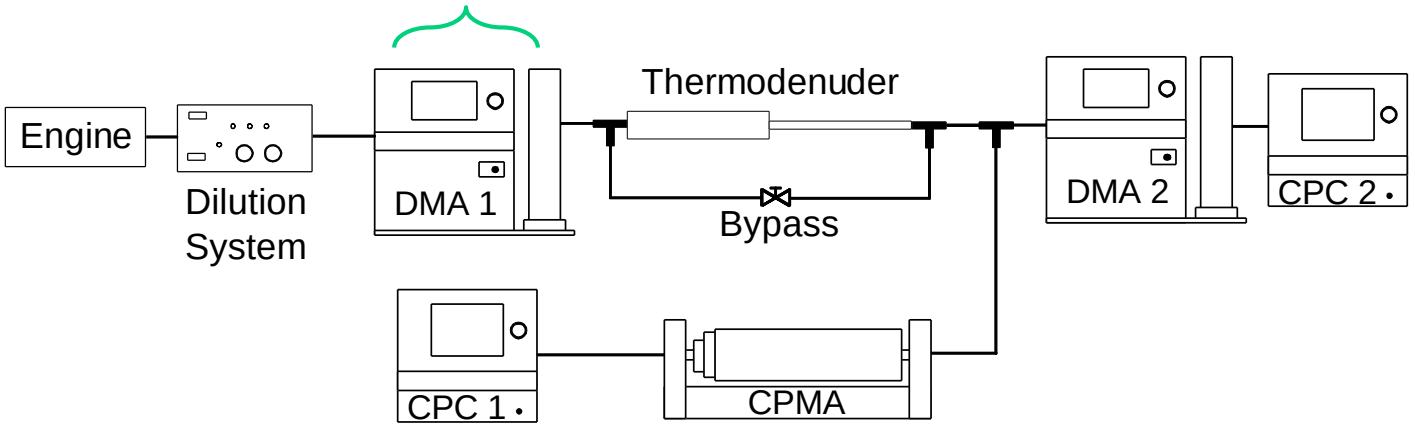
- 2 Liter, four cylinder, turbocharged spark ignition engine
- Wall-guided
- Fuelled with gasoline and ethanol blends
- Particles sampled after 3-way catalyst

Spark ignition engine

EXPERIMENTAL SETUP

- After dilution, particle mobility-equivalent diameter is set with DMA

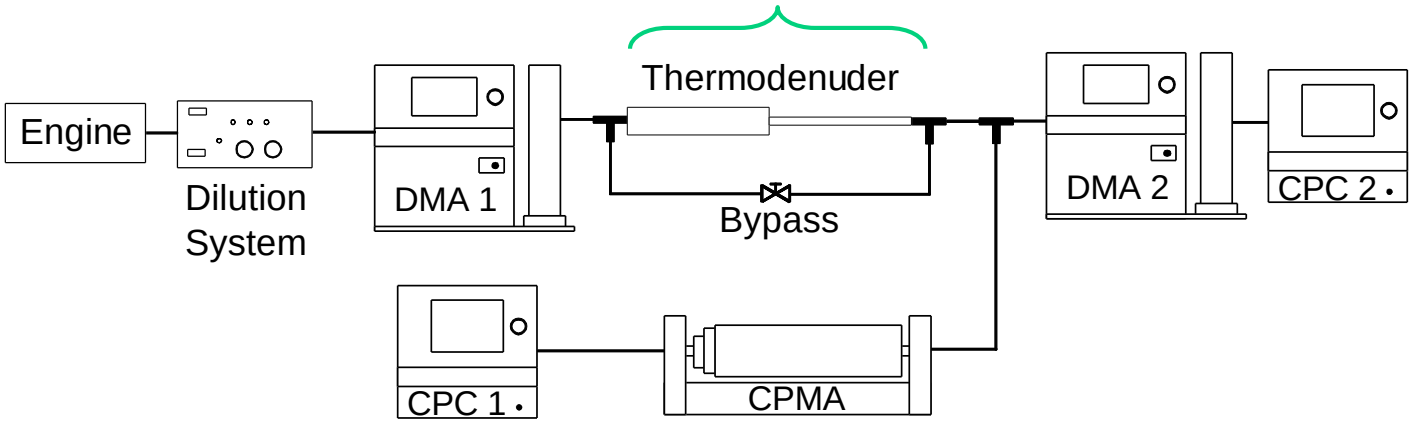




Experimental setup

EXPERIMENTAL SETUP

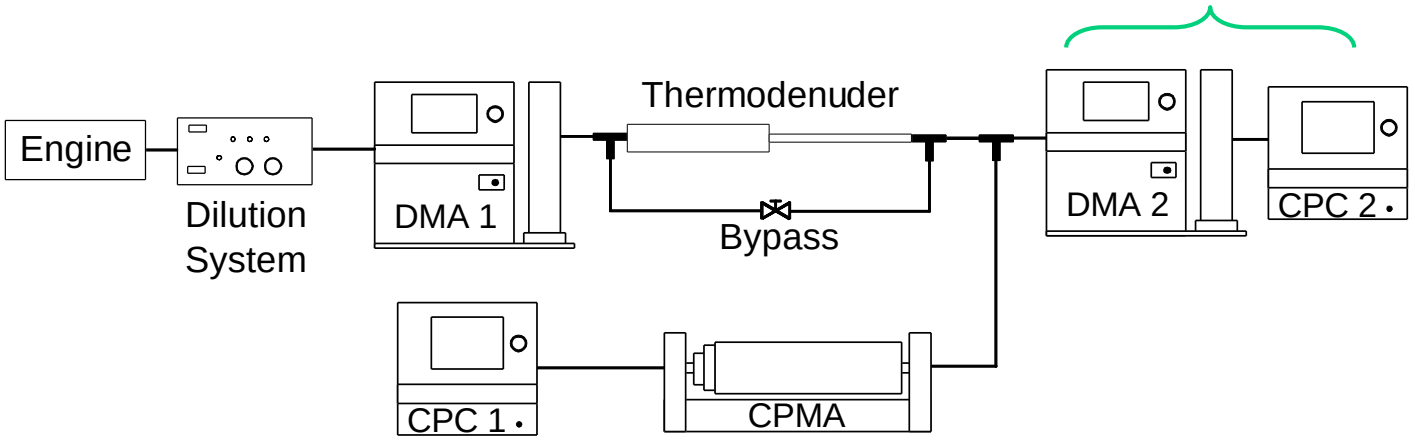
- After dilution, particle mobility-equivalent diameter is set with DMA
- Passed through thermodenuder or bypass



Experimental setup

EXPERIMENTAL SETUP

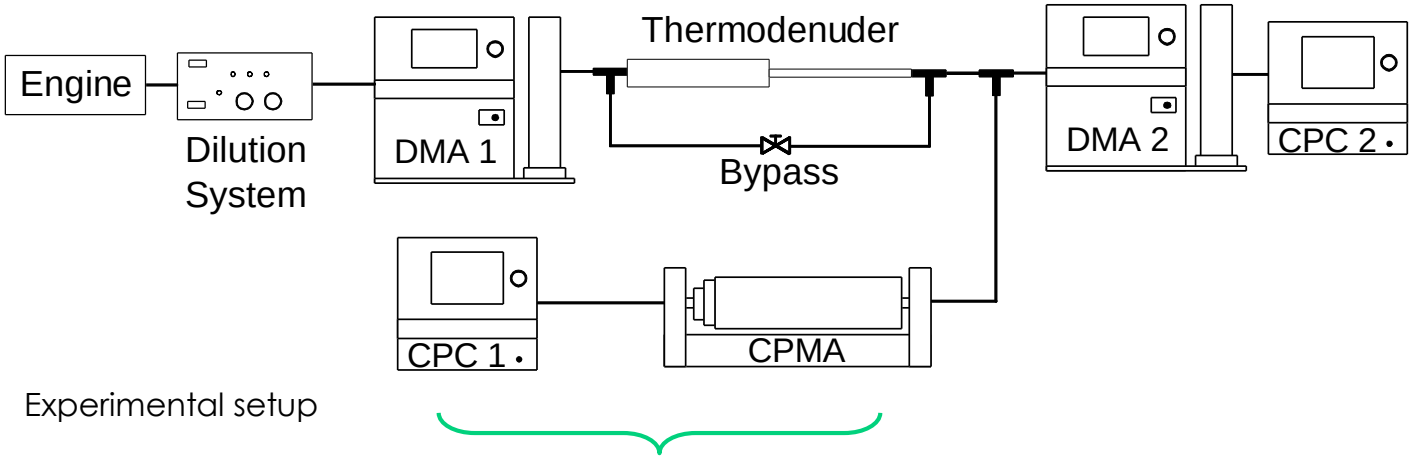
- After dilution, particle mobility-equivalent diameter is set with DMA
- Passed through thermodenuder or bypass
- Mobility-equivalent diameter measured with DMA and CPC (SMPS) – denuded size may be different than undenuded size



Experimental setup

EXPERIMENTAL SETUP

- After dilution, particle mobility-equivalent diameter is set with DMA
- Passed through thermodenuder or bypass
- Mobility-equivalent diameter measured with DMA and CPC (SMPS) – denuded size may be different than undenuded size
- Particle mass measured with CPMA and CPC



Experimental setup

TEST CONDITIONS – HPDI

- Six engine conditions tested
- Varied load and speed
- Also examined:
  - Exhaust gas recirculation fraction
  - Early cycle direct fuel injection for premixed charge

TEST CONDITIONS – GDI

- Three loads at 2250 RPM
- Idle condition (800 RPM, 0 N m)
- Gasoline mixed with 0%, 10%, and 50% ethanol (E0, E10, E50)

TEST CONDITIONS – GDI

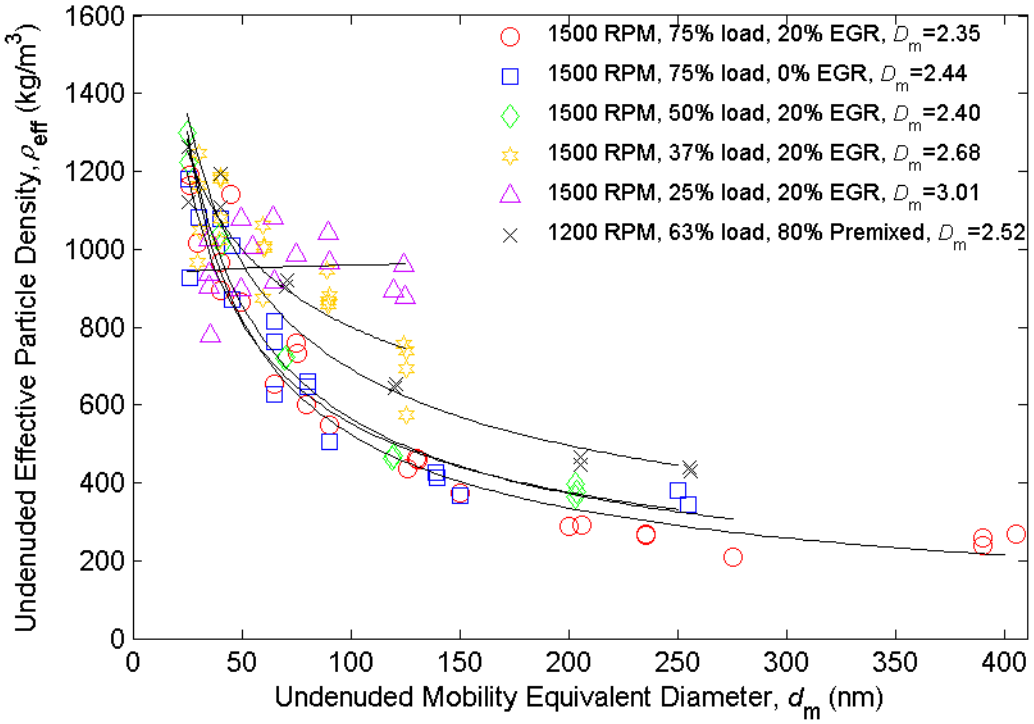
Property	Gasoline	Ethanol
Formula	C3 – C12	C_2H_5OH
Density (kg/m^3)	785	790*
Boiling Point, 10% (°C)	38.1	
Boiling Point, 50% (°C)	102.2	78*
Boiling Point, 90% (°C)	159.2	
AKI ((RON+MON)/2)**	91	100*
Aromatic Content (Volume %)	**44.3**	**0.0**
Isoparaffin Content (Volume %)	34.6	0.0
Napthene Content (Volume %)	4.8	0.0
Olefin Content (Volume %)	0.7	0.0
Paraffin Content (Volume %)	15.1	0.0
Oxygenate Content (Volume %)	**0.0**	**100.0**
Unidentified (Volume %)	0.4	0.0

*[1]

**Anti-knock index (AKI) is equal to the mean of the research octane number (RON) and motor octane number (MON)

HPDI RESULTS – EFFECTIVE DENSITY, UNDENUDED

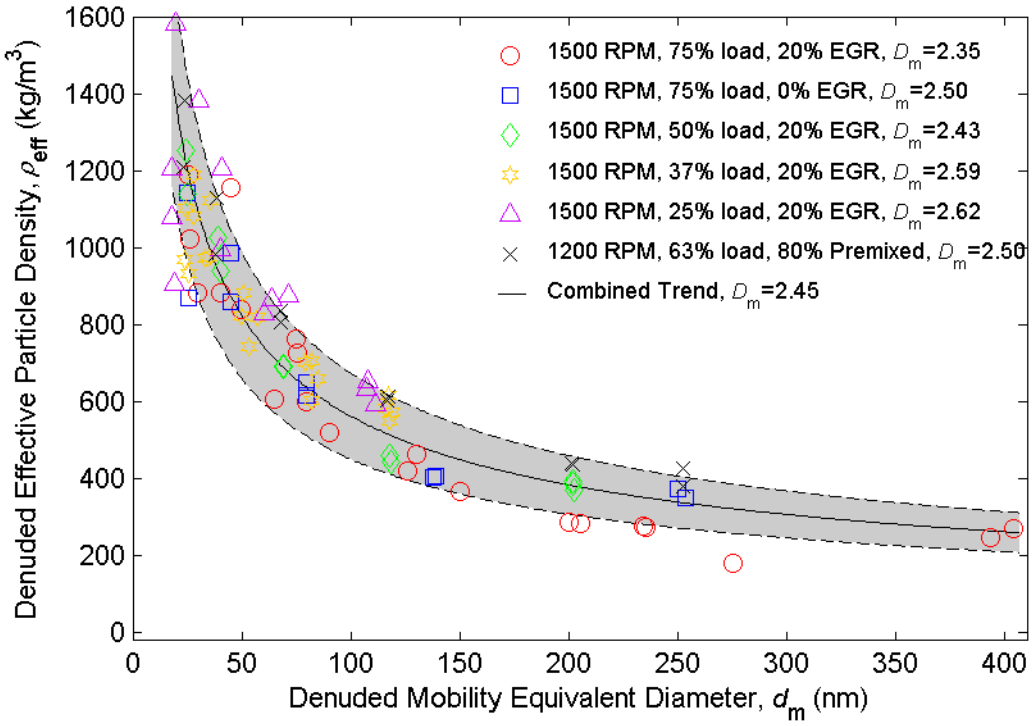
- 63% load (premixed), 37% load, and especially 25% load exhibit higher mass-mobility exponents
- Indication of liquid material



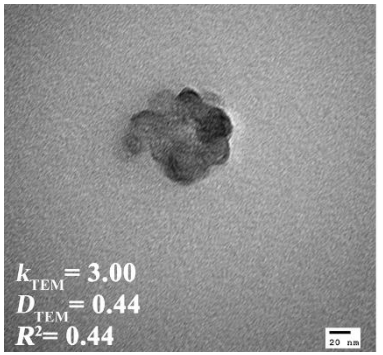
Effective density trends for undenuded trials

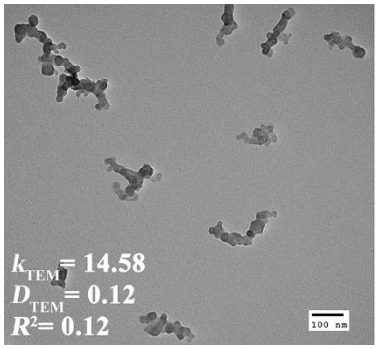
HPDI RESULTS – EFFECTIVE DENSITY, DENUDED

- Curves collapse to roughly the same line
  - D_m of 2.4 to 2.6
- D_m = 2.35 for previous diesel research ([2], [3], [4])
- Volatile material pulls soot into more compact shape [5]

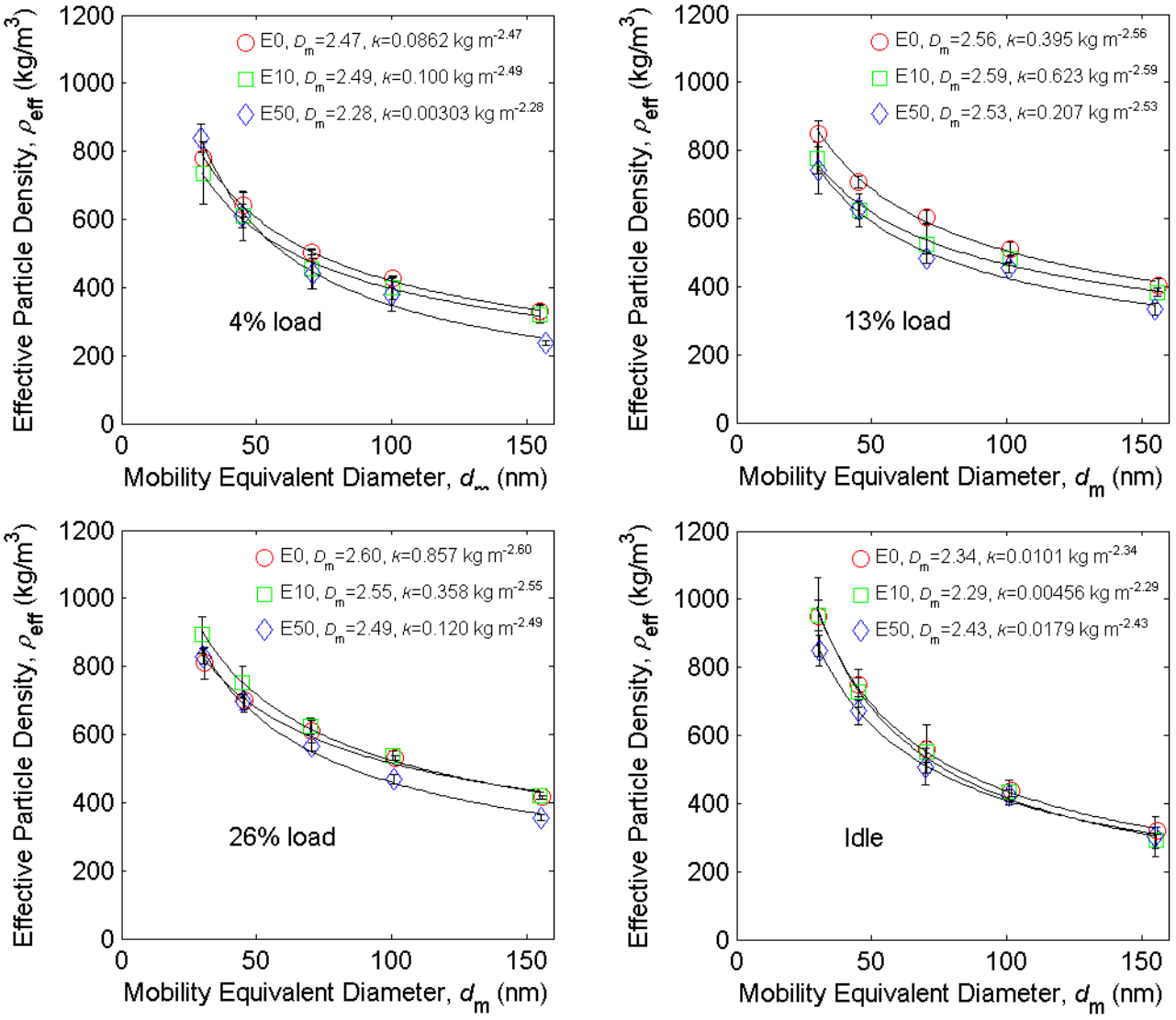


Effective density trends for denuded trials





GDI RESULTS – EFFECTIVE DENSITY



Effective density trends for denuded trials

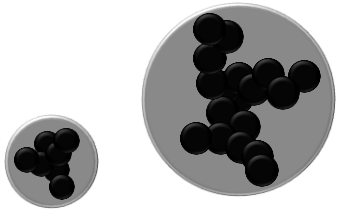
RESULTS – VOLATILITY

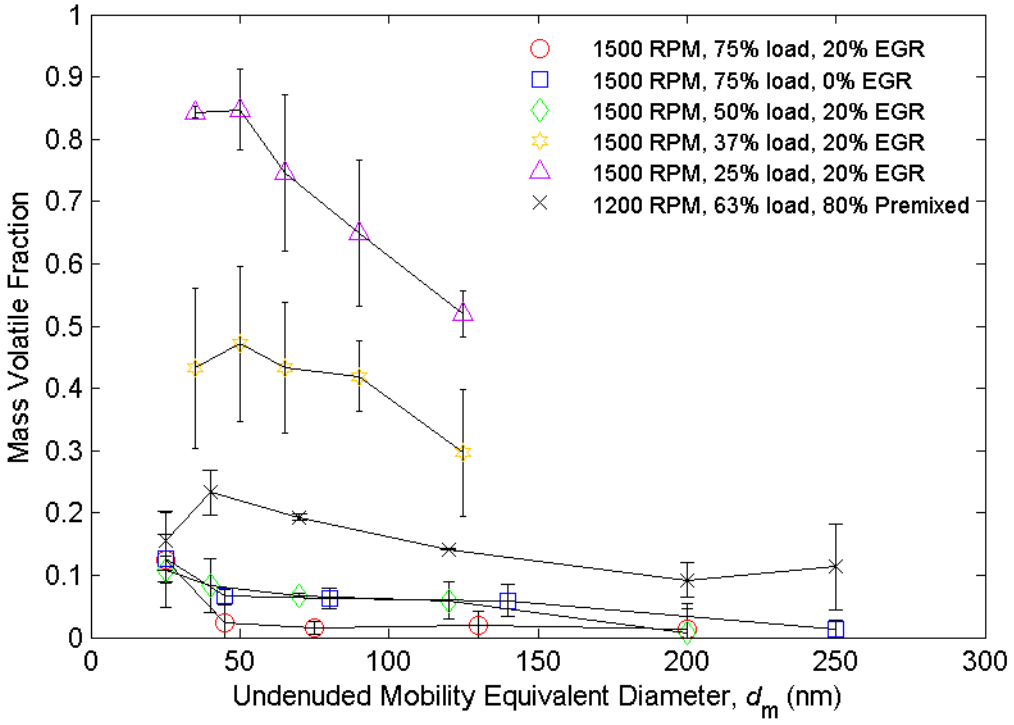
- Internally mixed particles contain volatile material condensed on a solid soot core
- Externally mixed particles will contain solid soot and separate droplets of volatile material

Contrast between internally (left) and externally (right) mixed volatile material

HPDI RESULTS – VOLATILITY, INTERNALLY MIXED

- Internally mixed particles contain volatile material condensed on a solid soot core
- Denuding decreases median diameter, but will not affect number concentration

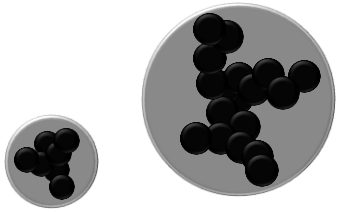


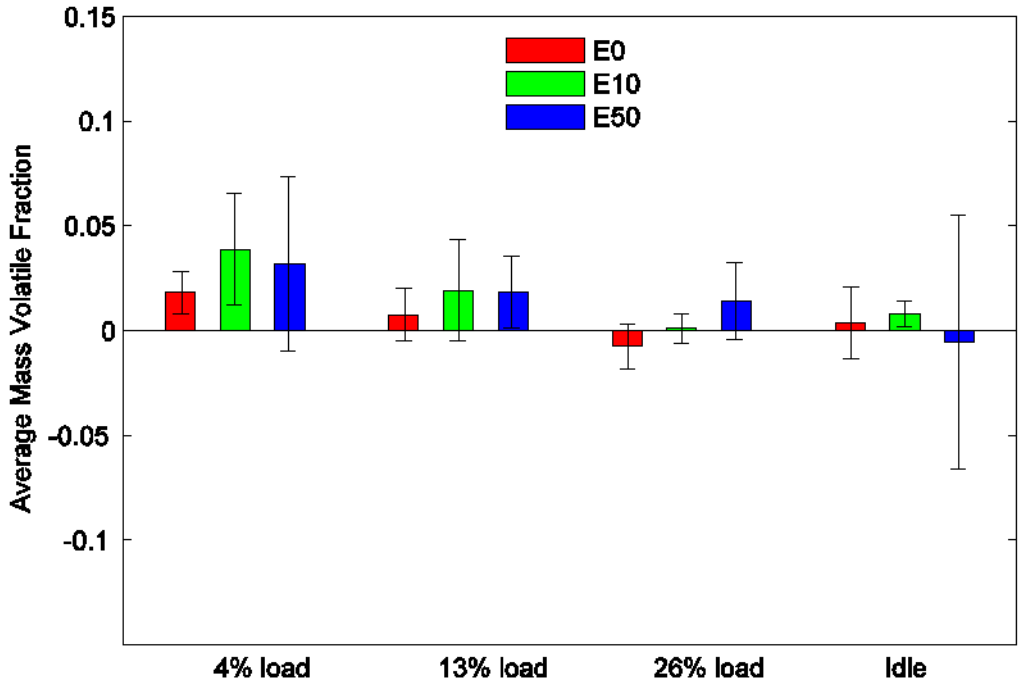


Size resolved mass volatile fractions

GDI RESULTS – VOLATILITY, INTERNALLY MIXED

- Internally mixed particles contain volatile material condensed on a solid soot core
- Denuding decreases median diameter, but will not affect number concentration

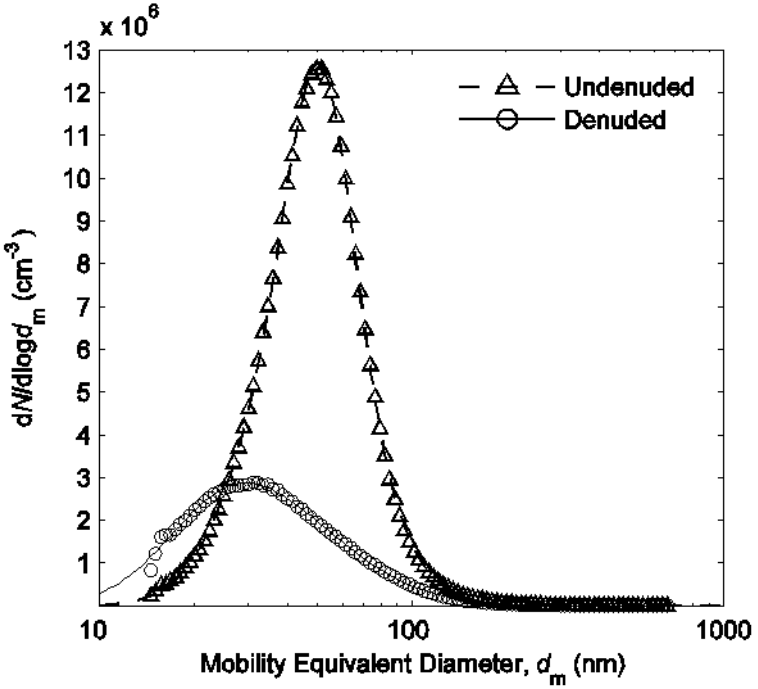




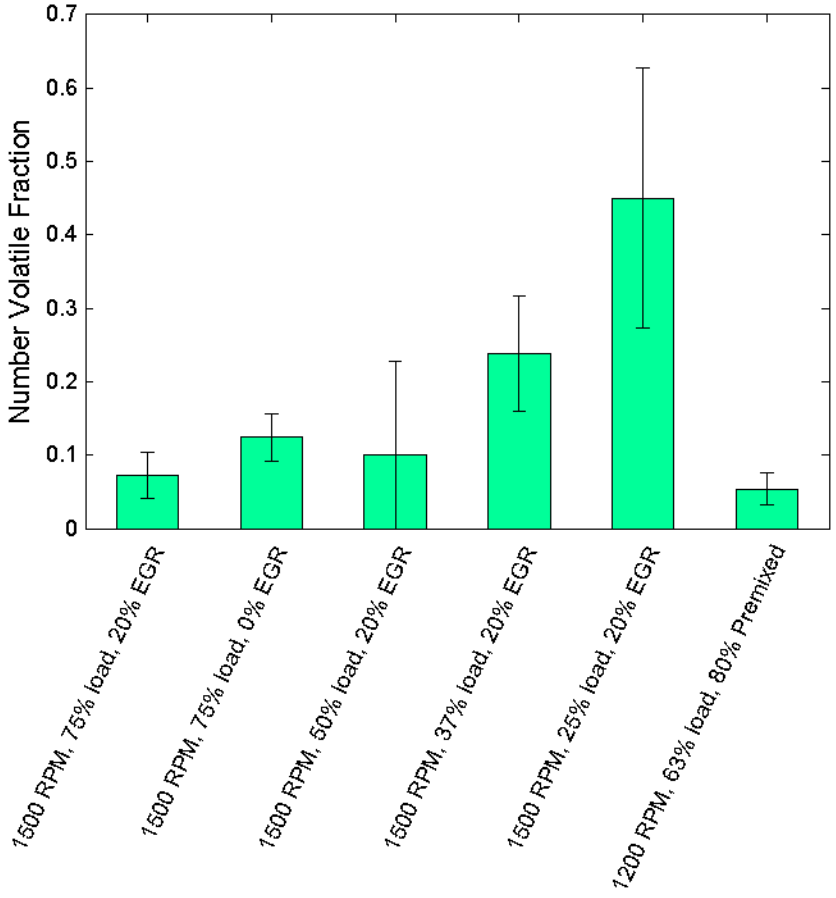
Average mass volatile fraction for all loads and fuels

HPDI RESULTS – VOLATILITY, EXTERNALLY MIXED

- Externally mixed particles will contain solid soot and separate droplets of volatile material
- Denuding will decrease number concentration



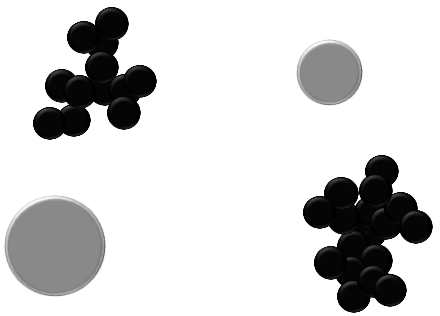
Denuded and undenuded particle number concentration for 1500 RPM, 25% load, 20% EGR

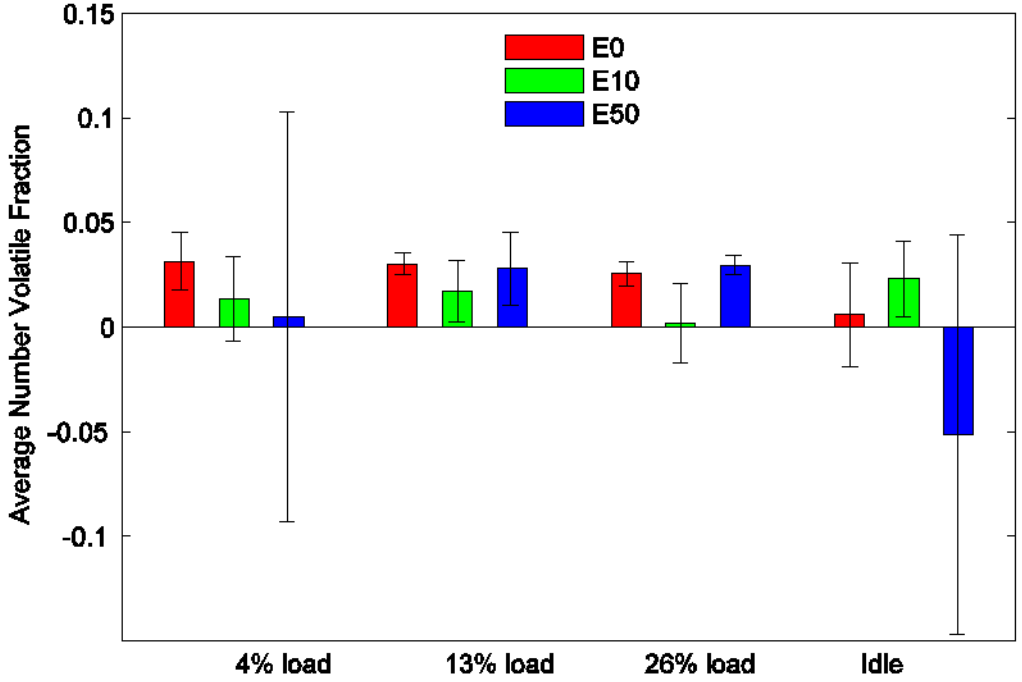


Overall volatile number fraction

GDI RESULTS – VOLATILITY, EXTERNALLY MIXED

- Externally mixed particles will contain solid soot and separate droplets of volatile material
- Denuding will decrease number concentration

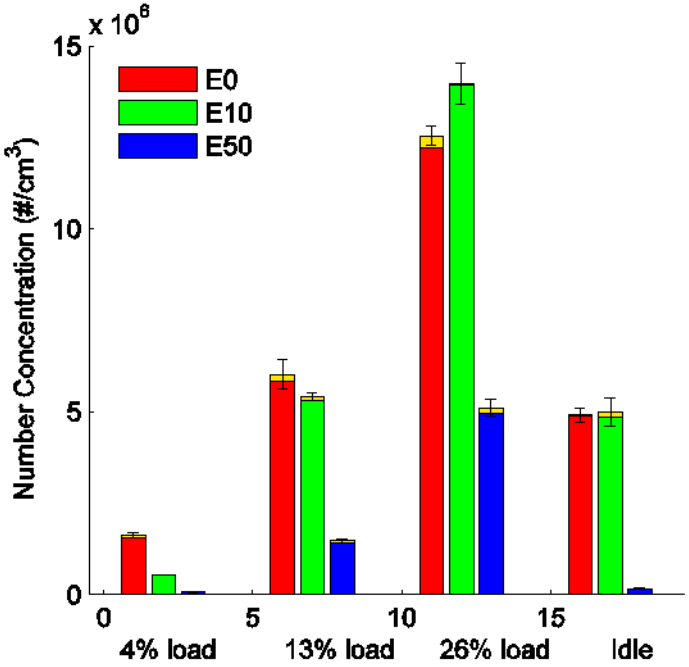




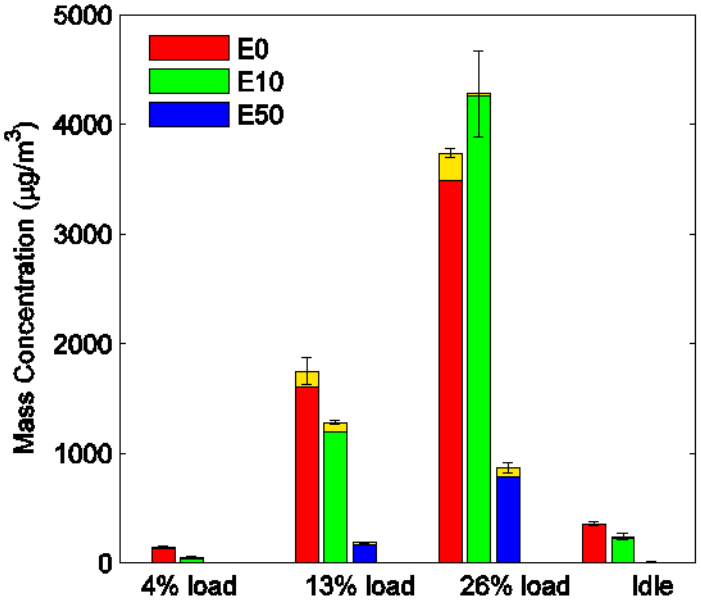
Average number volatile fraction for all loads and fuels

GDI RESULTS – NUMBER AND MASS CONCENTRATION

- Concentration increase with load
  - Idle similar to 13% load
- Ethanol reduces concentration
  - E10 can be similar to E0



Total number concentration. Yellow portion is volatile material



Total mass concentration. Yellow portion is volatile material

SUMMARY - HPDI

- All effective density trends collapse to roughly the same line when denuded
- Denuded mass-mobility exponents of 2.4 to 2.6
- Internally and externally mixed volatility highest at low loads
- Two particle species contained in single distribution

Acknowledgements:

NSERC CRSNG

Westport™

SUMMARY - GDI

- Mass-mobility exponents of 2.3 to 2.6
- Number and mass concentrations increase with load and decrease with ethanol fraction
- Low internally and externally mixed volatility

Acknowledgements:

NSERC CRSNG

Westport™

QUESTIONS?

REFERENCE MATERIAL

- [1] Catapano, F., Di Iorio, S., Lazzaro, M., Sementa, P., Vaglieco, B., "Characterization of Ethanol Blends Combustion Processes and Soot Formation in a GDI Optical Engine", SAE International. Doi: 10.4271/2013-01-1316

- [2] Westport Innovations Inc., "First Generation Westport HPDI Technology" http://www.westport.com/is/core-technologies/combustion/hpdi, accessed May 8, 2014

- [3] M. Maricq and N. Xu, "The effective density and fractal dimension of soot particles from premixed flames and motor vehicle exhaust," *Aerosol Science,* vol. 35, pp. 1251-1274, 2004.

- [4] K. Park, F. Cao, D. Kittelson and P. McMurry, "Relationship between Particle Mass and Mobility for Diesel Exhaust Particles," *Environmental Science and Technology,* vol. 37, pp. 577-583, 2003a.

- [5] J. Olfert, J. Symonds and N. Collings, "The effective density and fractal dimension of particles emitted from a light-duty diesel vehicle with a diesel oxidation catalyst," *Aerosol Science,* vol. 38, pp. 69-82, 2007.